THE KNEEHILLS TUFF

W.D.RITCHIE

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The undersigned hereby certify that they have read and recommend to the School of Graduate Studies for acceptance, a thesis entitled "The Kneehills Tuff", submitted by William Douglas Ritchie, B. Sc., in partial fulfilment of the requirements for the degree of Master of Science.

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April, 1957.

THE UNIVERSITY OF ALBERTA

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A DISSERTATION
SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
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OF MASTER OF SCIENCE

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by

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ABSTRACT

Petrographic and chemical studies were made of samples of Kneehills tuff from various outcrop localities in Alberta, between Cypress Hills in the south and Whitecourt in the north. The length and breadth of zircon crystals in each sample were determined and size-frequency curves constructed. A comparative study was made of samples and separates from late Cretaceous or early Tertiary tuff beds exposed in the Foothills area and a sample of rhyolite associated with the Boulder batholith in Montana.

Results of the investigations showed the Kneehills tuff to be uniform in texture, mineralogy and chemical composition over a wide area and almost identical to the upper tuff lenses above the Kneehills zone in the Drumheller area. It is suggested that the pyroclastic material for these tuff beds was derived from a late effusive phase of the Boulder batholith. Tuff beds of late Cretaceous or early Tertiary age exposed in the Foothills area were not the principal concern of this study, but in the few comparisons made, they do not appear to be directly related to the Kneehills type.

Radioactive dating of the zircon from the Kneehills tuff by the lead-alpha method yielded an age of __ million years. By the radiation damage method, the age is 110 $\pm$ 50 million years.

The potassium-argon age of feldspar from a bentonitic ash bed in the Ardley coal seam above the Kneehills tuff is 52 million years, a figure in good agreement with lead-alpha, lead-isotope and potassium-argon ages for the Cretaceous-Tertiary boundary.

Individual tuff lenses in the Kneehills zone appear to be wind carried material from separate explosive outbursts at the source.

The areal extent of each lens was controlled by late Cretaceous topography and meteorological conditions at the time of vulcanism. The original ash was apparently deposited in fresh water basins and altered diagenetically.

TABLE OF CONTENTS

FIGURES-TABLES-PLATES

CHAPTER ONE

INTRODUCTION

This study was undertaken for the purpose of establishing a probable source and an absolute age for the Kneehills tuff.

Samples of Kneehills tuff, possibly related tuff beds in the foothills area and a sample of rhyolite from Butte, Montana were studied.

Inasmuch as the Kneehills tuff is well dated paleontologically and marks the boundary between the Lance and pre-Lance beds, an absolute age would provide a valuable reference point for future work. For this reason, a carefully prepared zircon concentrate was sent to the United States Geological Survey for a lead-alpha date. As a check and with the aid of Dr. P. J. S. Byrne of the Alberta Research Council, an age was determined by measuring the amount of radiation damage in the zircon.

It seems worthy of note that this study provided an excellent opportunity to make use of a sample collection that required several years of collecting by the late Dr. R. L. Rutherford.

ACKNOWLEDGEMENTS

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The writer wishes also, to acknowledge the cooperation of those persons with whom he communicated personally in regard to occurrences and samples of the Kneehills tuff.

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PREVIOUS WORK

Although Selwyn (1873-74) first used the term "Edmonton" for the Upper Cretaceous coal-bearing strata near Edmonton city, it wasn't until 1886 that Tyrrell gave the name formation status in his description of the exposures along Red Deer River. Tyrrell included in the Edmonton formation all the continental coal-bearing beds overlying the marine Bearpaw formation up to and including the uppermost coal seam observed, namely, the Ardley seam, which is mined near Ardley, Alberta. He introduced the term 'Paskapoo' for the beds overlying the Edmonton on the North Saskatchewan River and considered them Paleocene in age.

Out of the interest in coal and a dinosaurian fauna contained in the Edmonton formation, much information has accumulated through Russell (1930), Allan and Sanderson (1945), Rutherford (1935-39), Sternberg (1947), Ower (1947) and others. Studies of the Edmonton formation and its counterparts in southern Alberta have been made by Williams and Dyer (1930), Russell (1932, 1948), Furnival (1946), Tozer (1952) and others.

The Kneehills tuff was noted but not recognized as a tuff until 1931 when Sanderson described it petrographically. Since that time, it has been found to be widespread over the plains of Alberta including some localities of which there is no record in the literature. Previous work on the Kneehills tuff as a discreet stratigraphic unit is lacking. Byrne (1951), however, made an attempt to determine the origin of the dark zone in which the Kneehills tuff occurs.

CHAPTER TWO

STRATIGRAPHY

Typical badland topography in various parts of Alberta is produced mainly by erosion of the Edmonton formation. This characteristic feature presents an excellent opportunity to study the formation in detail.

Sanderson (1945) proposed a three fold division of the Edmonton. The lower member includes 400 feet of beds between the underlying Bearpaw shale and a marine tongue of oyster bearing beds in the Drumheller area. The middle member comprises the beds from the marine tongue up to the top of the dark zone carrying the Kneehills tuff. The remaining beds underlying the Paskapoo comprise the upper member and contain a Triceratops fauna of Lance age (Sternberg, 1947). The middle and lower members yield a pre-Lance fauna.

Bell (1949), failing to recognize the marine tongue over a wide area, divides the Edmonton into a lower and an upper member with the division at the Kneehills tuff.

On the basis of electric logs supplemented by field observations Ower (1949) proposed a five-fold division of the Edmonton. His member A and the lower part of B are equivalent to the lower member of Sanderson; the upper part of member B, and members C and D are together equivalent to the middle member, and member E is equivalent to the upper member. Member D consists of from 6 to 20 feet of white bentonitic sandstone overlain by a 30 to 40 foot unit of dark brown bentonitic clay carrying tuff beds, designated by Ower as the Kneehills tuff zone. These two units have been conveniently referred to as the white and dark zones (Byrne, 1951).

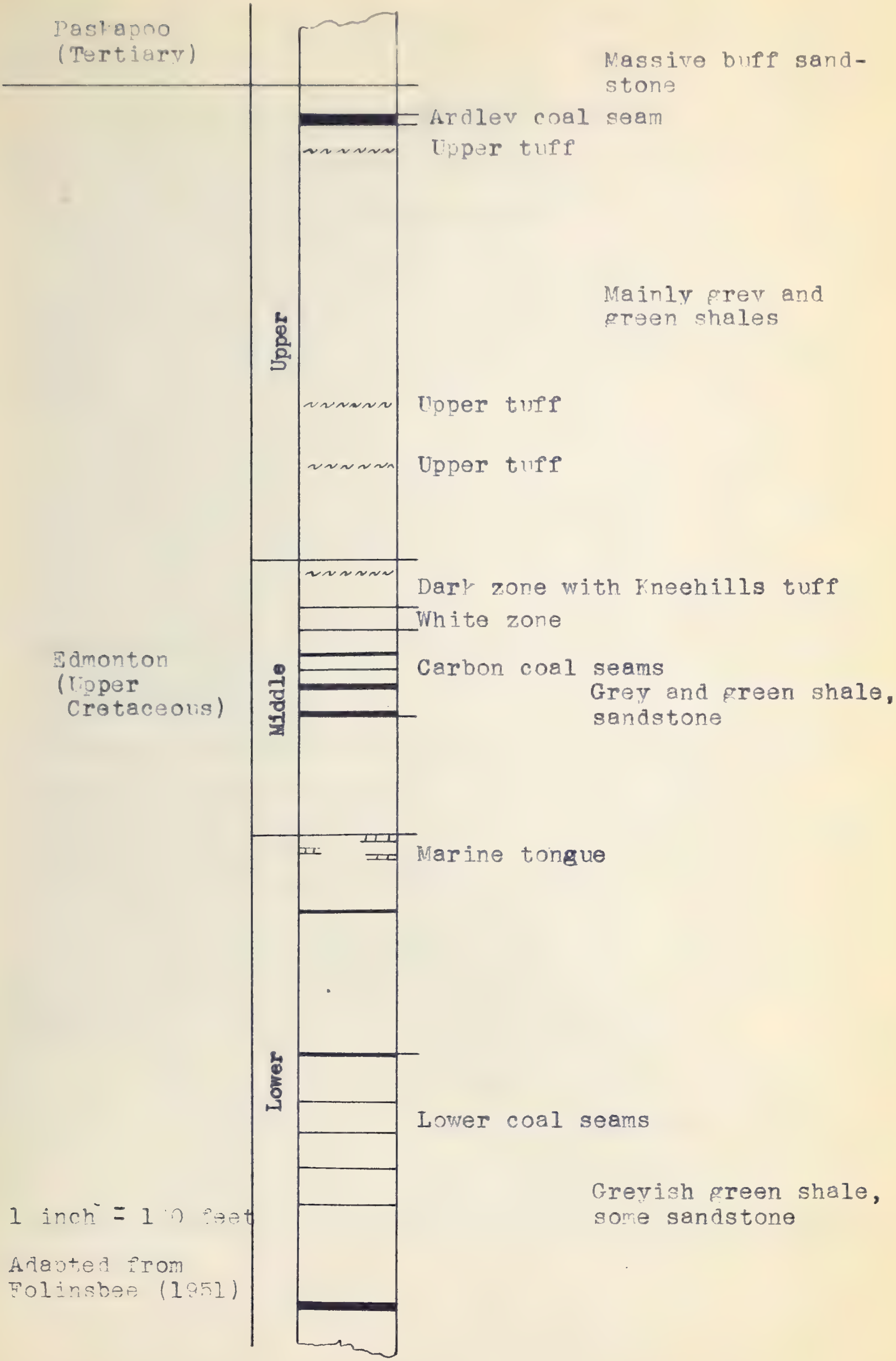
In the area between Red Deer and North Saskatchewan Rivers Ower finds a maximum thickness of 1700 feet for the Edmonton formation. The most striking lithologic features of the formation are the abundance of coal, bentonitic material and clay-ironstone concretionary forms. In general, these occur in a series of alternating poorly indurated shale and feldspathic argillaceous siltstone and sandstone. With the exception of the marine tongue, the entire formation represents continental deposition and may be deltaic in origin (Sanderson, 1941). Figure 1 is a generalized section of the Edmonton formation.

The Kneehills tuff may occur as a single bed less than 10 inches thick or may be present as two, three or four thin beds averaging less than 6 inches in thickness occurring over an interval of 5 or 6 feet in the upper part of the dark zone. In spite of this discontinuity the tuff is rarely absent. In hand specimen the tuff is light brownish grey, massive, hard and extremely fine-grained. It has a phonolitic ring when struck with a hammer, weathers to a light grey and forms a surface talus of sharp angular fragments.

The great lateral extent of the Kneehills tuff renders it a valuable marker horizon. It was used extensively for purposes of correlating coal seams in Red Deer valley. Caution must be excercised, however, when using the tuff as a marker owing to the presence of at least three identical tuff lenses occurring 68, 180 and 281 feet above the top of the dark zone. These upper tuff beds are always associated with a thin zone of dark shale varying in thickness from 10 to 15 feet (Folinsbee, 1951) and for this reason are easily confused with the Kneehills zone. The absence of an underlying white zone serves to

Figure 1.

GENERALIZED SECTION OF THE EDMONTON FORMATION
DRUMHELLER-ARDLEY AREA



distinguish them from the true Kneehills association. These upper lenses are known only at Drumheller (Folinsbee, 1951) and east of Trochu (Ower, 1949).

Outcrops of the Kneehills tuff are widespread. It was first identified by Sanderson (1931) a short distance east of Ardley on Red Deer River where it occurs about 240 feet below the Ardley coal seam. Since that time, Sanderson has located it in Hand Hills, in Wintering Hills, near Big Valley, near Carbon, on Kneehills and Threehills Creeks and at the head of Horshoe Canyon near the Calgary-Drumheller highway.

In western Cypress Hills area, tuff beds identical to the Kneehills were found but are not known to persist to the east. These tuffs also occur in a dark colored shale zone known as the Battle formation. The Battle is underlain by 25 to 40 feet of white bentonitic sandstone known as the Whitemud formation (Allan and Sanderson, 1945). On the basis of lithology and stratigraphic position the Whitemud formation has been correlated with the Colgate member of the Foxhills formation in Montana and the Dakotas (Fraser, 1935). The Battle formation of Cypress Hills is overlain by the Frenchman formation which is correlated by Furnival (1946) with the Hell Creek formation of Montana on the basis of a Triceratops fauna which is common to both. This tuff occurrence is undoubtedly Kneehills and marks the boundary between the Lance and pre-Lance beds (Sternberg, 1947).

The presence of Battle and Whitemud equivalents in the St. Mary River formation on Oldman River near Macleod, Alberta (Sec. 25, Twp. 10, Rge. 25, W4) was noted by Tozer (1952). The tuff here forms the boundary between the St. Mary River and overlying Willow Creek formation.

It is described as a light grey, very fine-grained porous rock which weathers to angular fragments that form a talus----"In thin section, this rock is seen to consist of small angular quartz and feldspar fragments embedded in an isotropic matrix" (Tozer, 1952). According to Tozer, the St. Mary River formation in this area may be correlated with the entire Foxhills stage. He assigns a Lance age to the lower part of the Willow Creek formation on the basis of paleontological evidence from other sections and suggests that the Edmonton-Paskapoo unconformity of the Bow River area (Rutherford, 1947) decreases in amplitude to the south and loses its identity on Oldman River. Rutherford reports an occurrence of tuff further upstream on Oldman River near Brocket (Twp. 7, Rge. 28, W4) which he considers identical to the Kneehills tuff. Since this ash bed occurs near the top of the Willow Creek, Rutherford suggested an Upper Cretaceous age for the entire Willow Creek formation. On the strength of Tozer's evidence, this tuff is later than Kneehills and probably early Paleocene in age.

Stewart (1943) and Furnival (1946) observed the white and dark zones together with the Kneehills tuff north of Gleichen, Alberta. This same assemblage was observed by Rutherford (1947) on Bow River west of Bartstow siding.

Northward, outcrops of the Kneehills tuff are known on Strawberry Creek, 30 miles southwest of Edmonton (Byrne, 1951). At this locality the tuff is present in its typical white and dark zone association. Byrne made a detailed stratigraphic study of the section. He measured 6 feet of white zone and 40 feet of dark zone in which three beds of tuff were found. Each tuff layer is overlain by a thin zone of light colored bentonitic material grading upward into the normal dark shale of the dark zone.

TABLE 1.

CORRELATION TABLE OF THE EDMONTON FORMATION

	Plains of Southwest Alberta	Plains of Southeast Alberta	West Central Alberta: Plains	West Central Alberta: Foothills		Montana and the Dakotas	Dinosaurian Fauna	Age
Tertiary	Porcupine Hills	Ravenscrag	Paskapoo	Paskapoo and Post-Brazeau beds	Saunders and Wapiti Groups	Fort Union		Thanetian
	Willow Creek (Upper)					Cannon Ball		Montain
				Entrance Congl.				Danian
Upper Cretaceous	Willow Creek (Lower)	Frenchman	Edmonton: Upper	Brazeau		Lance (Hell Creek)	Triceratops Tyrannosaurus Thescelosaurus Ankylosaurus	
	- tuff - -	- -tuff- -	Edmonton: Middle: -tuff- - -			Foxhills: Colgate Member	Arrhinoceratops Albertosaurus Hadrosaurus	Maestrichtian
		Battle	Edmonton: Middle: Dark Zone					
	St. Mary River	Whitemud	Edmonton: Middle: White Zone					
		Eastend	Edmonton: Lower					

Exposures of Kneehills tuff are know on Saskatchewan River near Genesee, Alberta and on Pembina River about 10 miles north of the Edmonton-Jasper highway in N.W. ¼ Sec. 13, Twp. 54, Rge. 7, W5. (Gleddie, 1957). They are known on Athabasca River downstream from Whitecourt in the southwest part of Sec. 12, Twp. 60, Rge. 12, W5. (Ower, 1949). In each case, the dark and white zones are associated.

A tuff bed was seen by Folinsbee (1957) on Smoky River about 5 miles above the junction with Kakwa River in Sec. 33, Twp. 64, Rge. 3, W6. Slumping obscurs the related beds but the interval is known to occur not far below two coal seams which he tentatively correlated with the Pembina seam to the south.

All exposures of which the writer is aware are described above. These occurrences are confined to the plains area of Alberta. What happens to the tuff westward into the foothills area is not known. However, McKay (1930) reports a 16 foot bed of tuff from the Saunders formation west of Edmonton. An excellent exposure may be seen a few yards west of the Canadian National Railway station at Coalspur, Alberta, where it comprises interbeds of hard unaltered tuff and thin beds of pure bentonite (Sanderson, 1931). This same bed has been traced from Pembina River to Gregg River in the Coalspur area, a distance of 20 miles. It occurs, according to Sanderson, about 800 feet below the Mynheer coal seam which is the lowermost commercial coal seam at Coalspur and Sterco. In 1943, McKay mapped these coal bearing beds as Edmonton formation, the underlying beds down to the marine Wapiabi formation as Brazeau and the beds overlying the coal series as Paskapoo. In 1945, in the Entrance area to the north, Lang mapped the Entrance conglomerate as the base of the Edmonton formation, some 800 feet below the lowest coal seam.

However, since that time Bell identified plant fossils collected by Lang (1946) and concluded that all the beds, including the coal series, down to the Entrance conglomerate are Paleocene in age. If this is correct, then the Saunders tuff is probably Paleocene in age and therefore stratigraphically higher than the Kneehills tuff. Stelck and Warren (1957) however, question the validity of Bell's conclusion. The query stemed from a study of the Genesee flora collected from the Triceratops zone of the upper Edmonton formation about 40 miles west of Edmonton on North Saskatchewan River. This flora indicates that the assemblage of Bell may not be restricted to the Paleocene but may also occur in the Cretaceous. The Genesee flora was described and figured by Brayton (1953).

L. J. Carr (1950) collected samples of a tuff exposed on Blackstone River 2 miles below the junction of Brown Creek. He mapped this horizon as late pre-Paskapoo. The tuff is reportedly associated with bentonitic beds.

LOCATION AND DESCRIPTION OF SAMPLES

The samples used in this study are mainly from the miscellaneous collection at the University of Alberta. These were collected or accessioned mainly by the late Dr. R. L. Rutherford over the past two or three decades. A few samples were collected by the writer during a field trip to the Drumheller area in October, 1956. Most, but not all of the outcrop areas mentioned in the discussion of stratigraphy are represented in this study. Samples were not available for a few localities.

Sample locations in Alberta are indicated by number on the index map (figure 2). The location of the rhyolite sample from Butte, Montana is not shown.

To avoid repetition and because the Kneehills tuff samples, irrespective of location, appear almost identical both in hand specimen and under the microscope, the same description, except for color, may apply to samples numbered one to nine inclusive. Significant changes in color of the fresh surface from one tuff sample to the next are recorded by comparison with the Rock Color Chart of the National Research Council (1948). A generalized description of the tuff follows.

Macroscopic Description:

The tuff varies in color from shades of brown to grey and weathers to a lighter color. It is hard, massive and very fine grained. When struck with a hammer it has a phonolitic ring; it breaks into sharp angular fragments. Weathered tuff in badland country forms a surface talus. In some cases the tuff shows features vaguely reminiscent of bedding but usually it is structureless. Vugs lined or filled either with chalcedony or bentonite can be observed with the naked eye.

Microscopic Description:

After examination of several thin sections, the writer could find little to add to Sanderson's (1931) original description --- "Microscopically this rock is seen to be made up of minute fresh, mineral fragments, quartz and feldspar mainly, with varying proportions of altered glass, all set in a felty groundmass which is isotropic to dimly anisotropic. In thin section conclusive tests of the matrix matter cannot be made. It is though that the groundmass is made up essentially of devitrified glass along with minute masses of fibres of redeposited chalcedonic or

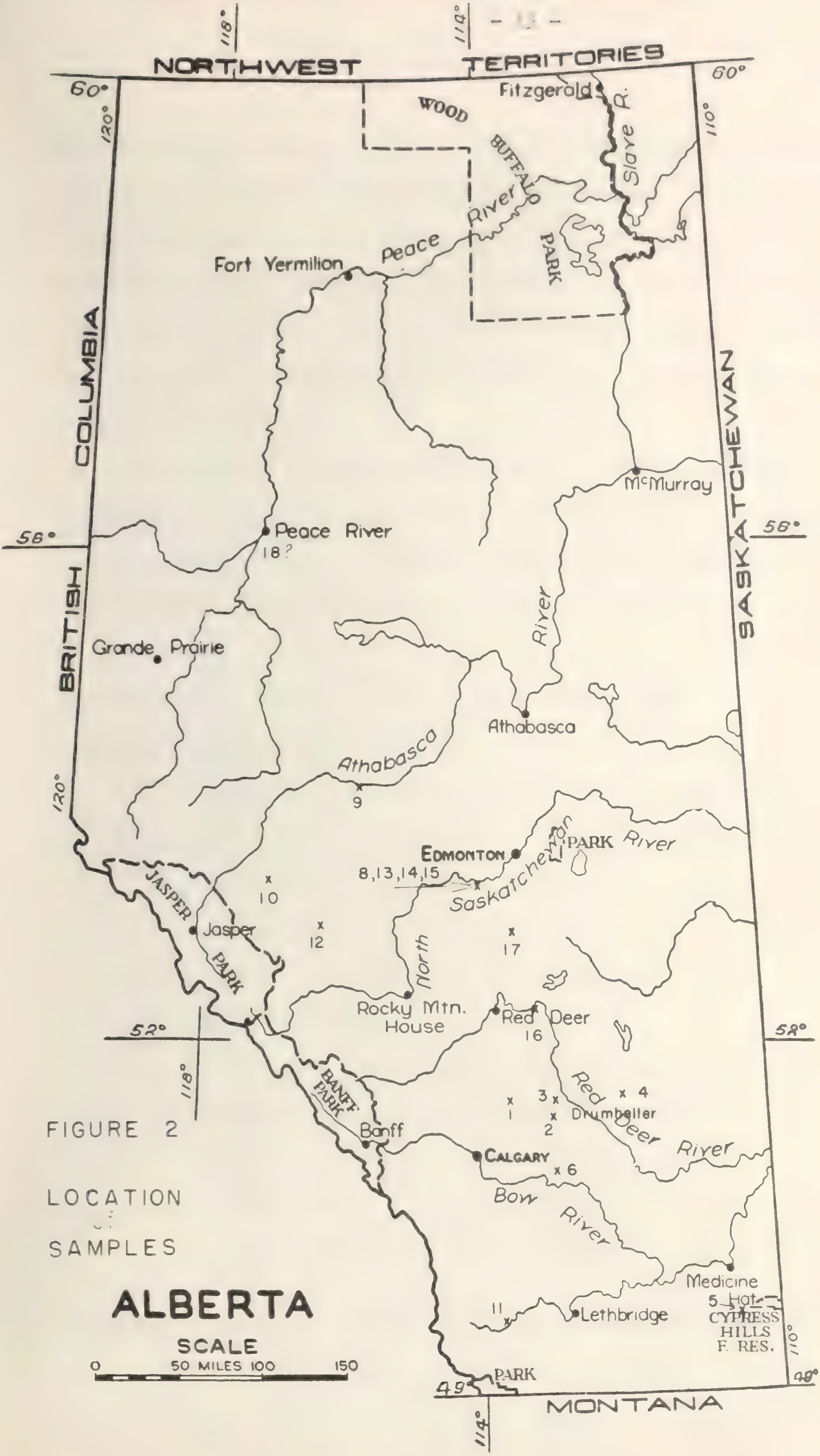


FIGURE 2

LOCATION OF SAMPLES

ALBERTA

opaline silica. The presence of vesicular, partly altered glass becomes apparent on close examination at high magnification. The characteristic shape of glass shards; long stringy fragments, crescentic bits of angular particles showing re-entrant angles, may be noted among the grains which remain isotropic under crossed nicols. The larger fragments range from 0.03 mm. to 0.05 mm. in diameter, and grade from this down to sub-microscopic sizes."

The feldspar fragments comprise both twinned and untwinned plagioclase. Stain tests for potash feldspar using sodium cobaltinitrite in the manner described by Chayes (1952) also showed fragments of micro-antiperthite in the form of minute orientated potash feldspar needles in plagioclase.

Classification: Vitric - crystal tuff (Heinrich, 1956).

Sample #1 - Kneehills Tuff (*2415)

Location: Outcrop 12 inches thick in stream bed of Threehills Creek 6 miles north of Carbon, Alberta (see plate 1).

NE $\frac{1}{4}$ Sec. 15 - Twp. 30 - Rge. 23 W4.

Collector: R. E. Folinsbee (1956)

Color: Light brownish grey (5YR4/1)

Sample #2 - Upper Tuff (2416)

Location: From upper-most tuff horizon, 270 feet above Kneehills zone about 6 miles north of Rosebud, Alberta.

Section 13 - Twp. 28 - Rge. 22 W 4.

Collector: W. D. Ritchie (1956)

Color: Light brownish grey (5YR4/1)

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* Numbers in brackets refer to specimen numbers in the University of Alberta collections.

Sample #3 - Kneehills Tuff (2417)

Location: Exposure at the head of Horseshoe Canyon near Drumheller.

Sec. 9 - Twp. 29 - Rge. 21 W 4.

Collector: W. D. Ritchie (1956)

Color: Light brownish grey (5YR4/1)

Sample #4 - Kneehills Tuff (2418)

Location: Outcrop near western edge of Hand Hills. This sample is from the upper of two beds which are 6 feet apart. There exists the possibility that this is an upper tuff horizon since the white beds were not observed.

NW $\frac{1}{4}$ - Sec. 36.- Twp. 29 - Rge. 18 - W4.

Collector: W. D. Ritchie (1956)

Color: Pale Yellowish brown (10YR5/6)

Sample #5 - Kneehills Tuff (2395)

Location: Sample collected from middle of three closely spaced tuff beds in western Cypress Hills. (see plate 1.)

Twp. 4 - Rge. 7 - W4.

Collector: Imperial Oil Geologist

Color: Light Olive grey (5Y6/1)

Sample #6 - Kneehills Tuff (2378)

Location: Outcrop northwest of Gleichen, Alberta. (see plate 1.)

Lsd. 3/4 - Sec. 25 - Twp. 22 - Rge. 23 W 4.

Collector: Not known.

Color: Brownish grey (5YR4/1)

Sample #7 - Kneehills Tuff (KA-27)

Location: Exposure located about 13 miles southeast of Big Valley, Alberta, 90 feet above Carbon coal seam.

Sec. 16 - Twp. 35 - Rge. 20 W 4.

Collector: J.O.G. Sanderson.

Color: Light brownish grey (5YR6/1)

Sample #8 - Kneehills Tuff (2421)

Location: Outcrop along Strawberry Creek a short distance downstream from the Telfordville post office.

SW¼ - Sec. 5 - Twp. 50 - Rge. 1 W 5.

Collector: P.J.S. Byrne (1950)

Color: Light brownish grey (5YR6/1)

Sample #9 - Kneehills Tuff (2003)

Location: Exposure along Athabasca River downstream from Whitecourt, Alberta.

Sec. 12 - Twp. 60 - Rge. 12 W 5.

Collector: J. Ower, California Standard Co. (1949)

Color: Light brownish grey (5YR6/1)

Sample #10 - Saunders Tuff (1765)

Location: Outcrop on Embarrass River at Coalspur, Alberta about 740 feet below a conglomerate zone.

Sec. 33 - Twp. 48 - Rge. 21 W 5.

Collector: H. Kunst, Imperial Oil Co. (1944)

Macroscopic Description: In hand specimen the rock is yellowish grey (5Y7/2), fine grained, extremely hard, and shows in some instances, distinctly laminated bedding features.

Microscopic Description: About 50 percent of the rock is composed of fresh angular fragments of feldspar, quartz and biotite together with numerous typically curved glass shards ranging in size from 0.5 mm. down. These are set in an isotropic matrix, presumably composed of glass and some secondary silica. Little trace of alteration or

devitrification is evident. Small cresentic bits of glass can be noted in the groundmass. The texture is much coarser than that of the Kneehills tuff (see plate 1).

Classification: Vitric-Crystal Tuff (Heinrich, 1956).

Sample #11 - Willow Creek Tuff (43-23)

Location: From exposure on Oldman River near Brocket, Alberta and in Upper Willow Creek beds (Tertiary).

Twp. 7 - Rge. 8 W 4.

Macroscopic Description: The rock is light olive grey (5Y6/1) fine grained, hard and massive.

Microscopic Description: Irregular quartz grains ranging from 0.15 mm. down to sub-microscopic size about 75 percent of the rock. Feldspar is present but is not abundant. The matrix consists of a dimly isotropic material which may be glass. Rounded zircons are common and various other accessory minerals such as epidote, garnet, sphene and opaque minerals can be seen in the thin section.

Classification: Tuffaceous siltstone.

Sample #12 - Tuff (112)

Location: Sample from an outcrop on the east bank of Blackstone River. The bed is intimately associated with bentonitic sandstone, probably late pre-Paskapoo in age (L.S. Carr).

Collector: L. J. Carr (1950).

Macroscopic Description: The rock is yellowish grey (5Y7/2) fine grained, well indurated and massive.

Microscopic Description: Crescentic shards and stringy fragments of glass less than 0.12 mm. in size form about 50 percent of the rock. These are set in a semi-isotropic groundmass which comprises

devitrified glass and clay. Quartz and feldspar fragments are minor, forming less than 10 percent of the rock.

Classification: Vitric tuff (Heinrich, 1956).

Sample #13 - Edmonton sandstone (2422)

Location: Sample from outcrop of sandstone a few feet above the Kneehills tuff on Strawberry Creek.

SW $\frac{1}{4}$ - Sec. 5 - Twp. 50 - Rge. 1 W 5.

Collector: P.J.S. Byrne (1950)

Binocular Description: The rock is a light grey speckled, fine to medium grained, kaolinitic, slightly calcareous, semi-friable, poorly sorted, sub-angular sandstone. Quartz grains are dominant and the dark grains are comprised of chert, carbonaceous flecks and argillaceous rock fragments. Feldspar makes up about 15 percent of the rock.

Classification: Greywacke (Pettijohn, 1949).

Sample #14 - Dark Zone (Byrne 7)

Location: Sample taken from a thin layer of light colored bentonitic material overlying and in contact with the middle tuff bed on Strawberry Creek.

SW $\frac{1}{4}$ - Sec. 5 - Twp. 50 - Rge. 1 W 5.

Collector: P.J.S. Byrne (1950).

Description: This clay zone is light colored and grades upward into the normal dark zone lithology. The zone is composed mainly of montmorillonite (Byrne, 1951). The grit fraction comprises 75 percent bleached and partially altered biotite, 20 percent quartz and 5 percent feldspar.

Sample #15 - Dark Zone (Byrne 8)

Location: Same exposure as sample #14 but about midway between the two upper tuff beds.

Collector: P.J.S. Byrne (1950).

Description: The sample is dusky brown, bentonitic, soft shale, composed mainly of iron rich montmorillonite. The coarse grades consist of 85 percent iron rich montmorillonite, 5 percent white clay mineral montmorillonite, 8 percent calcite and 2 percent quartz (Byrne, 1951).

Sample #16 - Ardley Bentonite.

Location: Sample taken from the upper part of the Ardley coal seam at Sisson's coal mine, one mile east of Heatburg, Alberta.

SE $\frac{1}{4}$ - Sec. 3 - Twp. 39 - Rge. 23 W 4.

Collector: W. D. Ritchie (1956).

Description: The bentonite layer is 3 to 4 inches thick and is overlain and underlain by coal. In color, it is moderate greenish yellow (10Y7/4). It is composed mainly of pure bentonite. The grit fraction is comprised of about 70 percent fresh angular quartz and 30 percent of a feldspar believed to be anorthoclase.

Sample #17 - Basal Paskapoo Sandstone (2367)

Location: Sample taken from a road cut west of Millet, Alberta.

Lsd. 8 - Sec. 20 - Twp. 47 - Rge. 27 W 4.

Collector: R. L. Rutherford (1936).

Description: The rock is fine-grained light grey speckled flaggy sandstone. Under the microscope angular fragments of quartz, feldspar and minor biotite are seen to comprise about 60 percent of the rock. These are set in a fine grained isotropic matrix of clay-like material. Scattered fragments of calcite, apatite, zircon and sericite together make up about five percent of the whole. Bedding or banding is evident in thin section and is formed by alternation between layers of clay with layers rich in feldspar and quartz. Although some volcanic material may be present as indicated on the label, none was noted.

Classification: Greywacke (Pettijohn, 1949).

Sample #18 - Nikinassin sandstone: Peace River area, Alberta.

Sample #19 - Rhyolite, Butte. (2423).

Location: This sample was collected during a field trip to Butte, Montana in 1929. The precise location is not known. It is, however, known that the rock is associated with the Boulder batholith and is, by field relationships, either a late phase or younger than the batholith proper.

Microscopic Description: The rock shows a porphyritic texture. Phenocrysts comprise 60 percent of the rock with 30 percent plagioclase, 20 percent quartz and 10 percent biotite. Feldspar fragments are zoned and twinned and are of the average composition of andesine. The biotite is finer grained than the quartz and feldspar and shows normal pale to dark brown pleochroism. The quartz phenocrysts are unstrained and contain inclusions of feldspar and biotite.

The matrix consists in part of fine grained quartz and a material showing a mottled aggregate structure under crossed nicols. on the basis of a strong positive stain test for potassium using sodium cobaltinitrite, the matrix is believed to be rich in potash feldspar.

Classification: Rhyolite.

CHAPTER THREE

HEAVY ACCESSORY MINERALS

Separations of heavy minerals were carried out primarily for the isolation of zircon but some study was made of the other accessory minerals.

SEPARATIONS

The hard fine grained tuff was crushed mechanically. Samples were first run through a jaw crusher and subsequently ground to a rather coarse powder by means of a pulverizer. The powdered sample was seived for 10 minutes using a U.S. Standard Sieve Series and the fractions remaining on the 100, 170, 200 and 270 mesh screens were retained. Heavy liquid separations on one sample for the various size fractions showed that the heavy mineral yield in the coarser size ranges, less than 100 but greater than 170 mesh, was negligible. For this reason only the material passing through the 170 mesh screen was used for mineral separations. For purposes of comparison, all samples herein reported were sieved on the same basis unless otherwise indicated.

Each sieved sample was washed in water to eliminate all clay size particles which tended to flocculate in the heavy liquids. Boiling the samples appeared to make little difference, therefore a kind of cold water panning process was employed, which proved to be fast and effective. Care was taken so as to avoid loss of coarse material.

In the case of bentonite samples, the grit fraction was separated by soaking the samples for a few hours in water followed by a series of decantations which reduced the total sample to a manageable quantity. Dispersing agent (Calgonite) was added and the sample placed in a Waring Blender for about fifteen minutes. The sample by this time was completely dispersed so that another series of decantations resulted in a clean grit residue.

After drying the samples, they were placed in 1000 ml. beakers into which 300 to 500 ml. of tetrabromoethane ($C_2H_2Br_4$; S. G. 2.9) was introduced. With thorough stirring at 15 minute intervals, the separation was complete after two hours. In order to attain maximum liquid recovery, the thick mat of light minerals forming at the top of the liquid was ladled off and placed in a filtering funnel attached to a vacuum pump. The remaining tetrabromoethane in the beaker was decanted into the funnel until only a few drops together with the heavy concentrate remained. This residue was washed onto a filter paper, using a wash bottle containing acetone, and then dried at 100°C.

Further separation of the residue was accomplished by placing it into a separatory funnel containing methylene iodide ($C_2H_2I_2$; S.G. 3.3). With stirring at short intervals to agitate the mineral grains which tended to come to rest on the side of the funnel, separation was usually complete after one hour.

The float fraction or those minerals with S.G. greater than 2.9 but less than 3.3 for this set of samples was small, consequently only one permanent arachlor (Index 1.66) mount was prepared for each.

The fraction heavier than S.G. 3.3, however, was split into magnetic fractions to facilitate identification of minerals and to isolate the zircon. Strongly magnetic material was removed from the residue by means of a hand magnet. This material consisted mainly of ilmenite and 'tramp iron' from the crushing equipment. The portion not attracted by the hand magnet was introduced into the Frantz Isodynamic Separator. A slope of 15 degrees and a tilt of 8 degrees was held constant for all the separations. Current strength settings of 0.2, 0.35, 0.45, 0.74, 1.2, and 1.5 amperes, following Hutton (1952), were used for one sample in order to determine the settings with the largest yields.

To eliminate those settings with essentially no yield and thereby minimize loss due to handling, settings of 0.2, 0.5 and 1.5 amps proved to be adequate.

The concentrates from these latter settings, including the one rejected at 1.5 amps, were split (except when all the sample was used), mounted in arachlor and examined microscopically.

The heavy mineral content of the M[illegible]cehills tuff is low. The average heavy mineral index (S.G. greater than 3.3) for a washed sample in the 170 to 270 mesh size range is 0.10 percent by weight.

For the tuff samples in general, about 50 percent by weight of the total heavy concentrate (S.G. greater than 3.3) was drawn off by the hand magnet. This strongly magnetic material consists mainly of tramp iron, magnetic ilmenite, and, minor magnetite.

Ten percent of the residue was magnetic at 0.2 amps. This fraction comprises mainly ilmenite.

At 0.5 amps, about 20 percent of the total concentrate was magnetic. Ilmenite is most abundant here with lesser amounts of pyroxene, amphibole, epidote, and biotite.

Usually less than 5 percent of the concentrate was affected by a field strength of 1.5 amps. The main minerals appearing in this fraction are sphene, zircon containing magnetic inclusions, rutile and leucoxene.

Approximately 15 percent of the total residue was rejected at 1.5 amps. This is the main zircon fraction. In the tuff samples, pyrite is the only other mineral present in this fraction in any significant amount except in rare instances when poor separations were made and apatite failed to float in methylene iodide.

MINERAL IDENTIFICATIONS

Inasmuch as the separations were performed primarily for the purpose of zircon studies, only a cursory examination was made of the remaining accessory minerals. For complete description and illustrations of accessory minerals from the upper Cretaceous and Tertiary beds of the Western Canada Basin, the reader is referred to Beveridge (1956).

Table 2 is a cursory accout of the heavy minerals present in most of the samples used in connection with this study. It is evident that all the Kneehills samples (1 to 9 inclusive) carry a suite which is fairly consistent, the main minerals being ilmenite, zircon, apatite, pyrite, and titanite. Of these, ilmenite and zircon are by far the most abundant. Slight inconsistencies are to be expected in those minerals which are present in trace amounts.

The foothills tuff samples (10,11 and 12) are well as the sandstone samples (13 and 17) are aberrant in that they contain notable amounts of tourmaline, garnet, epidote and clinozoisite. With no attempt at interpretation at this point, other features which seem significant are; the scarcity of zircon in the tuff from Blackstone River (12); the apparent absence of apatite and biotite in the Ardley bentonite (16); and the abundance of clinozoisite and epidote in the sandstone (13 and 17).

On a biotite free basis, the Butte rhyolite (19) suite, with the exception of chalcopyrite, is similar to the Kneehills suite. Only one other sample run was noted to carry a comparable amount of biotite, the sample from the light coloured bentonite zone overlying the middle tuff bed at Strawberry Creek (#7). This sample is not included in table 2.

TABLE 2.

RELATIVE ABUNDANCE OF HEAVY MINERALS

SAMPLE NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	16	17	19
Amphiboles	–	–	–	–	x	–	–	x	–	–	x	x	x	x	xx	x
Apatite	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	–	xx	xxx
Biotite	–	x	x	x	x	x	x	x	–	x	x	xx	x	–	xxx	*xxx
Clinozoisite	–	–	–	–	–	–	–	–	–	–	–	xx	x	–	x	–
Epidote	x	x	x	x	x	x	x	–	x	–	xx	xx	x	x	x	x
Garnet	–	–	x	x	–	–	–	xx	–	–	x	x	x	x	xx	x
Pyroxenes	x	–	x	x	–	x	x	x	–	x	x	x	–	x	xx	x
Rutile	x	x	x	x	x	x	x	–	x	x	xx	xx	x	x	x	–
Titanite	xx	x	x	xx	x	x	x	x	x	x	xx	x	x	x	x	x
Tourmaline	–	–	–	–	–	–	–	–	–	xx	–	x	x	x	xx	–
Zircon	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xx	xxx	xxx	xx	xxx
Magnetite	x	x	x	x	x	x	x	x	x	x	x	x	xx	–	x	x
Ilmenite	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xx	xx	x	xx
Leucoxene	–	x	–	–	x	x	–	xx	xx	x	x	–	x	–	x	–
Pyrite	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	x	–	x	x	x	x
Chalcopyrite	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	xxx

xxx Abundant (over 10%)

xx Common

x Rare to a trace

– Not observed

* Biotite in the Butte rhyolite is so abundant that it is not strictly an accessory mineral; relative abundance of the other minerals is rated on a biotite free basis.

Ilmenite, being both consistent and abundant in the samples, deserves some description. It is variably magnetic and is found in the magnetic fraction from the hand magnet as well as from field strength of 0.2 and 0.5 amps on the magnetic separator. Ilmenite crystallizes in the tri-rhombohedral class of the hexagonal system and occurs in the heavy concentrates as flat tri-rhombohedrons (plate 2). In reflected light, it is black like magnetic but differs from magnetite in its crystal form and weaker magnetism.

Ilmenite is best studied in reflected light under a binocular microscope using a high power of magnification; the crystal form can then be readily observed.

Identification on the basis of crystal form was confirmed by running an x-ray diffraction pattern on the ilmenite from one of the tuff samples and comparing it with a pattern from a known ilmenite (plate 2). As can be observed, the two patterns are identical.

Ilmenite readily alters to leucoxene. Pseudomorphs of leucoxene after ilmenite are common in some of the samples.

Ilmenite separated from the rhyolite sample from Butte is identical to that of the Kneehills tuff.

ZIRCON STUDIES

A study of zircon crops from the Kneehills tuff at several widely separated localities on the plains of Alberta show them to be almost identical. The typical Kneehills zircons are colorless or an almost imperceptible shade of pink. They are, in general, normal prismatic to slightly stubby, doubly terminated euhedra. Combinations

of first and second order prisms with complex terminations are in the majority although some are simply terminated with a single pyramid or, more rarely, with a well developed pinacoid (001). Long prismatic euhedra are few in number. Inclusions are present in most of the euhedra and they comprise, in part, rod shaped apatite crystals which may or may not show a preferred orientation parallel to the c-axis. Other types of inclusions equally if not more abundant are dark spherical gas and/or liquid inclusions. Still other inclusions are present, some of which are responsible for the weakly magnetic properties of some of the crystals.

Zonary structures are rare and fissured zircons are absent. Outgrowths were not observed in any of the crops but rare twins (010 compositions plane) were noted.

Most of the euhedra exhibit sharp solid angles especially on the prisms but some have slightly rounded terminations. Zircons which are distinctly rounded form less than 10 percent of the zircon concentrate.

According to Poldervaart's (1956) observations, rounding by magmatic corrosion is more common in effusive rocks. It is believed that these rounded crystals are the result of corrosion in the magma chamber from which the tuff was derived. The possibility that they may in part represent contamination by detrital material at the time of deposition, of course, cannot be overlooked; the presence in trace amounts (less than one percent) of small rounded hyacinth zircons in the various crops can be accounted for in no other way. The rounded hyacinths are similar to those described by Beveridge (1956).

STATISTICAL STUDY

Most of the past work on zircons has been done on granitic rocks. Many attempts have been made to characterize granites by the habit, elongation, inclusions or color of their zircons (Taylor, 1937; Groves, 1930; Reed and Gilluly, 1932; Dapples, 1940). Poldervaart (1956) emphasizes the danger in comparing common zircon characteristics such as lack of color or prismatic habit of one granite zircon concentrate with another. Properties such as these exist in zircons of most granites and on this basis Archean granites might be correlated with Tertiary granites. Tests made by Poldervaart on several observers for a detailed classification scheme resulted in numerous inconsistencies in the less conspicuous zircon characters and in features present only in minor amounts. He found that results could be brought into agreement by simplifying the scheme to include unmistakable and easily recognized zircon characters. Unfortunately, few granites stand out as having distinct zircon qualities. In addition, Poldervaart concludes, "Quantitative classifications of zircon concentrates are at all times to be preferred to qualitative classifications of zircons. Measurements of crystal size seem particularly helpful". He demonstrates the fact that zircon studies of igneous rocks are used to best advantage to show petrogenetic relationships of the rock and that they should not be used for purposes of correlation unless accompanied by other independent evidence.

In order to eliminate bias and errors in judgement which almost invariable accompanies a qualitative classification, measurements on individual crystals were undertaken for the prime purpose of placing the study on a reproducible statistical basis.

MEASUREMENTS AND RESULTS

Maximum length (L) and breadth (B) of individual crystals were measured by aid of a micrometer eyepiece. In the case of rounded grains, the long dimension was measured regardless of whether or not it corresponded to the c-axis. Broken crystals were excluded from the count. Tests on zircon breakage in the laboratory were conducted by Poldervaart (1955) who concluded that small crystals were essentially unaffected by sample crushing and less than 10 percent of the large ones were broken.

Readings were recorded in columns for length and breadth. A third column was used for elongation (L/B). Each column was then treated according to Smithson (1939), that is, by calculating frequency percent for the average of four consecutive micrometer units and moving two units each time. Corrections applied by Smithson for the exageration of the number of large crystals encountered in a direct traverse were eliminated here because all the crystals were measured in each of several fields at various places on the slide. Average scale unit values used for lengths and breadths were converted to millimeters and plotted against frequency percent. No conversion, of course, was required for the elongation values since they are pure numbers independent of size. Each zircon crop, then, was represented by three curves, length, breadth and elongation.

The curves of all the Kneehills samples were constructed on the basis of 200 measured crystals. Samples used for comparison purposes were based on 100 zircon measurements. Curves for all the samples used are present in Figure 3. For the sake of convenience, they are arranged in order of number as indicated on the location map (figure 2).

Two sets of curves for sample #1 were constructed to illustrate the fact that inclusion of zircon crystals from the coarse grade sizes

of the Kneehills tuff only emphasizes the maxima on the elongation curve.

Curves for samples one to nine inclusive exhibit an unmistakable family resemblance. The reason for the bimodal character of the elongation curves is not entirely clear. Certainly a large percentage of rounded crystals would produce such a split effect but these are not present in that amount. Variation in the position and amplitude of the maxima may be due to the greater error incurred in measuring the elongation of crystals less then 0.03 mm. in breadth. It seems more likely that the maxima are real, at least in part, and represent two zircon types whose elongation were determined by magmatic conditions, possibly analogous to an early and a late stage of crystallization. Such bimodal curves are shown by Poldervaart (1956); they appear to be more typical of the finer grained more silicic igneous rocks.

Since the presence of rounded and sharply euhedral crystals in approximately equal amounts can produce bimodal curves, interpretation of the curves without some knowledge of the general zircon characteristics is apt to be misleading. For example, the Willow Creek sample (#11) shows curves similar to the Kneehills type but examination of the zircon crop reveals a high percentage of rounded crystals, the hyacinth variety included. The Nikanassin sample (#8) contains zircons which are almost exclusively well rounded with abundant hyacinths. This curve, as might be expected, shows only one maximum with low elongation.

Zircon measurements for the tuff from Blackstone River (#12) indicate a Kneehills type, however, they are conspicuously etched. The zircon yield of the sample was low, consequently only 100 crystals were measured. The crystals, unlike the Kneehills, are dirty and show, in many cases, irregular boundaries due to adherring bits of matrix rock.

This resulted in a number of anomalously large breadth measurements. These crystals with false breadth measurements have low elongations and would consequently contribute to the first of the two maxima.

The thin zone of bentonite clay overlying the tuff bed at Strawberry Creek (#14) is considered by Byrne (1951) to represent alteration of the tuff bed. Examination of the zircons together with size-frequency curves indicate that this is probably true. Zircon from the overlying dark zone (#15), however, contain a much larger zircon riddled with inclusions and in some instances highly etched. The curves are not strictly comparable to the Kneehills type.

Two sets of curves for the rhyolite from Butte (#19) are shown; one set for the zircon separated from all the material passing through the 100 mesh screen and the other set for the size range between 170 and 270 mesh. The curves for the former exhibit large crystals with bimodal elongation, the maximum value falling at 2.2. By restricting the sieve range for the second set of curves in an attempt to duplicate Kneehills sizes, it can be seen that the elongation curve is still bimodal but the maxima are shifted to the left. The length and breadth curves, though also shifted to the left, still indicate the presence of appreciably larger crystals than those which are typical of the Kneehills tuff. Restricting the sieve range is not comparable to either sorting by air or primary crystallization of smaller crystals but it serves to suggest the existence of a petrogenetic relationship between the Kneehills tuff and the rhyolite from Butte, Montana. Zircons from the rhyolite are, in all characteristics with the exception of size, remarkably similar to the Kneehills zircons (see plates 3 and 4).

None of the several elongation curves shown by Taubeneck (1957) for various rock types from the Bald Mountain batholith in Oregon shown bimodal character.

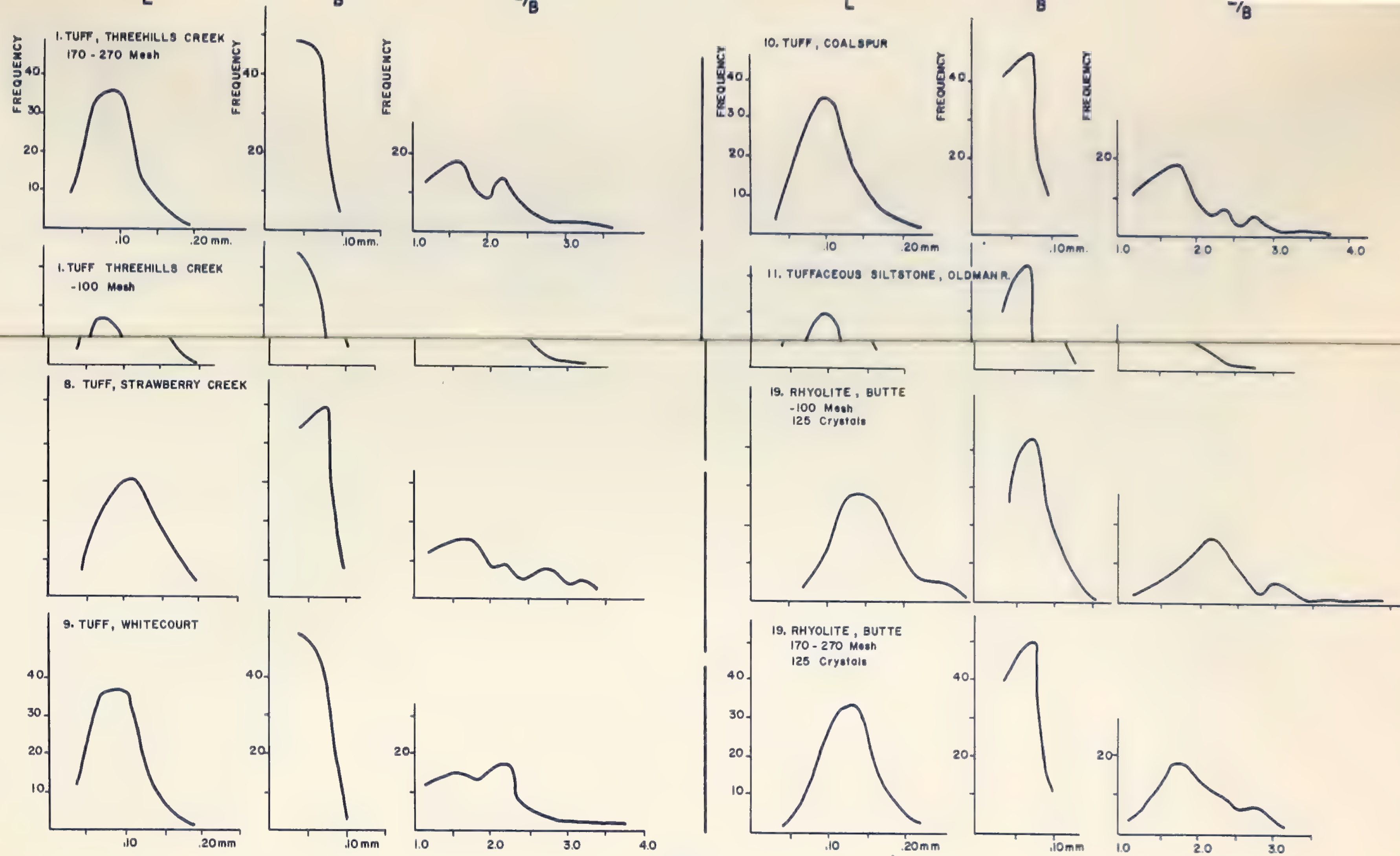


Figure 3

ZIRCON SIZE - FREQUENCY CURVES

EACH SET OF CURVES IS BASED ON MEASUREMENTS OF 200 CRYSTALS RECOVERED FROM GRADE SIZES LESS THAN 170 MESH BUT GREATER THAN 270 MESH UNLESS OTHERWISE INDICATED

CHAPTER FOUR

CHEMICAL DATA

A representative sample of the Kneehills tuff from Threehills Creek (#1) was sent to the Rock Analysis Laboratory, University of Minnesota for a common constituent analysis, reported as follows: (Analyst, Doris Thaemlitz)

SiO_2	87.81
Al_2O_3	5.54
Fe_2O_3	0.68
FeO	0.24
MgO	0.51
CaO	0.51
Na_2O	0.77
K_2O	0.84
H_2O+	1.11
H_2O-	1.24
CO_2	0.09
TiO_2	0.54
P_2O_5	tr.
MnO	0.004
Total	99.88%

Sanderson (1931) reports essentail oxide analysis of tuff samples from Drumheller and Cypress Hills as follows: (Analyst, Wm. Gerrie)

	Drumheller	Cypress Hills
SiO_2	87.0	89.6
Al_2O_3	4.8	3.6
CaO	1.5	1.2
MgO	2.0	2.0
K_2O	0.7	0.4
Na_2O	0.9	0.4
Ignition loss	2.8	3.4
Total	99.7%	100.6%

A comparison of the three analyses leaves little doubt as to their chemical identity. The most striking feature is, perhaps, the common high silica content.

Normative constituents for the Threehills Creek analysis, calculated according to the C.I.P.W. method (Johannsen, 1931), are as

follows:

Orthoclase	....	4.35
Albite	....	7.45
Anorthite	....	1.30
Enstatite	....	1.52
Apatite	....	tr.
Calcite	....	0.24
Sphene	....	0.32
Ilmenite	....	0.48
Hematite	....	0.50
Corundum	....	3.43
Excess Silica	....	79.50
	Total	99.09%

Some consideration was given the known mineralogy of the rock in the calculations of the norm. Much of the excess alumina which is expressed as corundum, however, is probably present in the clay mineral montmorillonite. The presence of montmorillonite, presumably as a result of alteration of the tuff, was established by running an x-ray diffraction pattern on the particles less than 2 microns in diameter. These particles comprise the material remaining in suspension in the top 10 cms. of water after five hours of undisturbed settling.

The high excess silica value is due, in part, to the presence of secondary silica in the form of chalcedony in small vugs which can be readily observed with the naked eye. Sanderson (1928) considers most of the excess silica as secondary and states that it was leached from adjacent beds. Byrne (1951), however, could find no mineralogical difference between the beds adjacent to the tuff and the remainder of the zone. The writer suggests that leaching and alteration of some of the original constituents in the tuff bed itself resulted in enrichment of silica, in part precipitated as chalcedony. In all probability, the bed was originally quite high in silica, undoubtedly rhyolitic in nature. An analogously high silica content in the Mowry shale of the Black Hills

region is generally considered to have originated, in some way, from the alteration of volcanic ash (Rubey, 1929). Altered rhyolites recorded by Washington (1917) from Iron Pot Basin, Yellowstone Park and De Lamar Mine, Idaho also have high proportions of silica as well as similar proportions of the other common constituents.

A few of the unweathered tuff samples were analysed for the oxides of sodium and potassium with a Perkin Elmer model 146 Flame Photometer using a lithium internal standard. The results are tabulated as follows:

Sample No.		$\%K_2O$	$\%Na_2O$
1.	(Kneehills tuff, Threehills Creek)	0.83	0.74
2.	(Upper tuff, Drumheller)	0.64	0.52
3.	(Kneehills tuff, Horseshoe Canyon)	0.67	0.63
4.	(Kneehills tuff, Hand Hills)	0.55	0.59
5.	(Kneehills tuff, Cypress Hills)	0.36	2.25
6.	(Kneehills tuff, Gleichen)	0.20	0.31
7.	(Kneehills tuff, Big Valley)	0.60	0.45
10.	(Saunders tuff, Coalspur)	2.63	1.04
11.	(Willow Creek tuff, Brocket)	0.98	0.50

A comparison of the results obtained for the sample from Threehills Creek (#1) with those of the same sample obtained in the chemical analysis of essential oxides on page 35 show good agreement. However, the soda value obtained here for the Cypress Hills sample as compared to the value reported by Sanderson is discordant. With this one exception, the sodium and potassium content of all the Kneehills type samples (1 to 7 inclusive) is uniformly less than one percent. The Saunders tuff (#10) on the other hand, is considerably higher in both constituents.

These results are interpreted as being indicative of remarkable chemical uniformity for the Kneehills tuff over a wide area.

CHAPTER FIVE

GEOCHRONOLOGY

RADIATION DAMAGE

It is well known that crystal structure damage by internal radioactive bombardment can produce a metamict state in several minerals. Of the several minerals that contain trace amounts of the radioactive elements uranium and thorium, zircon is considered by most workers to be best suited for dating by measurements of radiation damage.

Hurley and Fairbairn (1953) state that these radioelements can be distributed in the zircon crystals in three ways. Firstly, they may be uniformly distributed throughout the crystal as a result of introduction into the structure at the time of crystallization. Secondly, they may be variably present in concentric zones due to changes in conditions during crystallization of the zircon. Lastly, they may be contained in other radioactive minerals present as inclusions.

Radioactive disintegration of these radioelements and the consequent emission of alpla and beta particles and gamma rays results in the dislocation of atoms from their normal lattice positions. Beta particles and gamma rays probably have negligible affects (Seitz, 1952). Most of the energy accompanying emission of alpha particles is expended in ionization but a small portion is expended in collision and subsequent displacements of atoms. Atoms are also displaced simultaneously by recoil nuclei. Such dislocations affect the optical properties, specific gravity, hardness, resistance to solvents, infrared spectrum and x-ray diffraction pattern of the zircon. These changes can be used to measure radiation dosage which is the quantity of radiation received per unit weight of the irradiated material. Irradiation commences at the time of crystallization and if the rate can be determined, the time elapsed since the start of irradiation can be computed.

Holland (1954) states that this principle of age dating can be applied only if the relation between radiation dosage and radiation damage is constant throughout geologic time and annealing of the structure damage is either zero or constant with the past history of the material. In addition, he states that the rate of irradiation must have been constant or related by some predictable expression to the present rate of irradiation.

Radiation dosage δ, has been expressed by Beveridge (1956) adapted from Holland (1954) as

$$\delta = AF \qquad (1)$$

where A is the present alpha activity in alphas per milligram per year and F the factor allowing for the decay rates of the uranium series. F is expressed as:

$$F = \frac{8\,(e^{\lambda 1 t}-1) - 7/139\,(e^{\lambda 2 t}-1)}{8\;1 - 7/139\;2} \qquad (2)$$

where $\lambda 1$ and $\lambda 2$ are the decay constants for U^{238} and U^{235} respectively; t is the total time of radiation in years.

The correction for thorium applied by Holland is omitted here on the basis of Gottfried's (1954) work with Ceylon zircons; he showed that almost all the radioactivity in these zircons is due to uranium and its daughter elements.

The hardy qualities of zircon and its occurrence in most rock types render it particularly suitable for age dating. Metamict crystals of zircons are characterized by measurable increases in lattice dimensions and measurable decreases in refractive index and density. It is generally agreed that the most accurate index of radiation dosage is obtained by measurement of increased lattice dimensions using x-ray diffraction methods. The measurements usually used are either the C_o dimension of the unit cell (Holland, 1954) or, the one used in this suudy, the diffraction angle 2θ on the 112 plane for Cu- α radiation (Hurley and Fairbairn 1953).

Changes in optical properties, notably, refractive index, are slight in the early stages of metamictization but considerably greater in the latter stages consequently only the older zircons are determined with any degree of accuracy when applying this method as an index of radiation dosage.

The use of density to determine radiation dosage is limited by the difficulty of obtaining accurate measurements on naturally occurring zircon (Hurley and Fairbairn, 1953).

The relationship between C_o and radiation dosage has been calculated by Holland; one is a straight line function of the other. C_o ages are, by comparison, generally smaller than 2θ ages, the difference being greater in the more damaged crystals (Beveridge, 1956).

The method of determining radiation dosage by measuring the 2θ diffraction angle on the 112 plane was used in this study in an attempt to establish an absolute age for the Kneehills tuff. Hurley and Fairbairn (1953) determined a relationship between 2θ angles and radiation dosage which is presented graphically in figure 4. According to procedures outlined by these authors, it was found that both precision and accuracy of results were improved by introducing a silicon internal standard with the zircon. Silicon produced a sharp diffraction peak at 28.466° (2θ) which was measured at the same time and on the same mount as the unknown. Measurements were made by Hurley and Fairbairn on zircons from a number of samples for which lead-alpha and lead-uranium ages were known thus enabling them to construct a fairly accurate curve of 2θ values versus radiation damage.

PROCEDURE

One-half gram of zircon was separated from the 170-270 mesh size fraction from 75 lbs. of tuff from Threehills Creek (#1) using heavy

[illegible]

liquids and a magnetic separator as previously described. After splitting the zircon sample, half was prepared for a lead-alpha age determination by removing the pyrite. Unless totally removed, the primary lead in the pyrite would distort the spectographic analysis for total lead. By heating the sample to 450°C in a furnace for 10 minutes the pyrite was made magnetic and removed with a magnet. The sample was further hand-picked with a wetted camel's hair brush. The final pure aliquot was sent to the U.S.G.S. for a total lead-total activity age.

The remaining sample was prepared for alpha counting and x-ray diffraction work. This sample was not heated owing to the danger of annealing. Although the sample was hand-picked, minor pyrite remained in a negligible amount for purposes of x-ray diffraction work.

The present alpha activity of the zircon was determined by making beta counts using a shielded beta counter. The sample was run against a U.S.G.S. standard zircon of known alpha activity.

The conversion from beta to alpha counts is based on the assumption that radon leakage in the uranium decay series for the standard zircon and the unknown is either negligible or the same for both samples. Most of the beta emmissions are from the daughter elements formed in the latter part of the decay series following the radon stage.

The zircon sample was placed in a small brass container 1.5 mm. in depth and having an inside diameter of 5 mm. The container was filled level with the top and smoothed. All excess zircon on the outside of the container was removed before introducing the sample into the counter. Two runs were made on different days. During the first run, ten minute counts were taken alternately for background, U.S.G.S. standard zircon, and Kneehills zircon in that order. The second run was made taking one hour counts for each sample and one-half hour background counts at the beginning and at the end of the run. Extreme care was taken in reproducing the geometry of the set-

[illegible]

up for each count. The results of both runs are tabulated as follows:

	Background		Gross Beta Count			
			U.S.G.S. Standard Zircon (202α/mg./hr.)		Kneehills Zircon.	
Run		Time (mins.)		Time (mins.)		Time (mins.)
1	206	10	280	10	329	10
	210	10	282	10	337	10
	202	10	245	10	327	10
	213	10	265	10	331	10
Run 2	630	30	1585	60	1940	60
	646	30				
Total	2107	100	2657	100	3264	100
Net Beta Count			550		1157	

Optimum reproducibility of results is best obtained by utilizing a thick source, that is, a thickness corresponding to some point on the flat portion of the curve in figure 3a. It is doubtful if the 1.5 mm. thickness

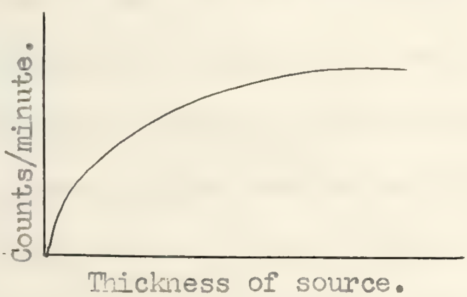


Figure 3a. Beta activity as a function of source thickness for fixed geometry.

used here constitutes a thick source. Sufficient sample was not available to determine the minimum thickness of a thick source. However, the results indicate that, although the source used may not have been a thick one, some point on the curve corresponding to the thickness used was reproduced with almost negligible variation.

The same container was used for both zircon samples and variation in degree of packing of the samples seems to have had little effect on the gross beta counts.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Using the net beta counts for a total of 100 minutes on the basis of 202 α/mg. hr. for the standard zircon, the alpha activity of the Kneehills zircon is:

$$\frac{1157}{550} \times 202 = 425\ \alpha/\text{mg./hr.}$$

The high background compared to the net count for the standard zircon results in a standard error of:

$$\frac{\pm\sqrt{2657 + 2107}}{550} \times 100 = 12.7 \text{ percent.}$$

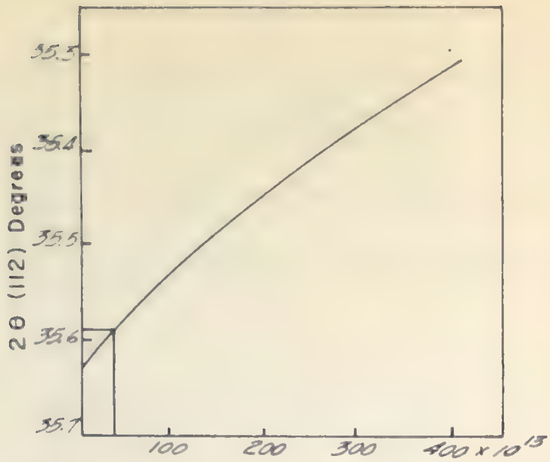
For the Kneehills zircon the error is 6.3 percent. Assuming a negligible error in the alpha activity of U.S.G.S. standard, the total possible error for the alpha activity of the Kneehills zircon is 19 percent.

The value 425 α/mg./hr. was then corrected for whole crystal emmission which allows for the alpha particles emerging from fine crystals before coming to rest. Facilities for such a correction measurement are not available at the University of Alberta, as a result, an average value on a percentage basis was calculated from the figures listed by Hurley and Fairbairn (1953). The correction value arrived at for the Kneehills zircon is 70 α/mg./hr. The corrected alpha activity for tuff zircon is 55 α/mg./hr. or 31 x 10^5 alphas per milligram per year.

Dr. P. J. S. Byrne of the Alberta Research Council determined the 2θ diffraction angle on the 112 plane for the Kneehills zircon following the procedure set forth by Hurely and Fairbairn. Instead of a silicon internal standard, however, he used a sample of piezoelectric Brazilian quartz, probably the purest naturally occurring quartz known. The 2θ value reported is $35.59^{\circ} \pm .02^{\circ}$ with a corresponding d spacing of 2.5193 ± 0.0015. This 2θ value was used in figure 4 to obtain a value

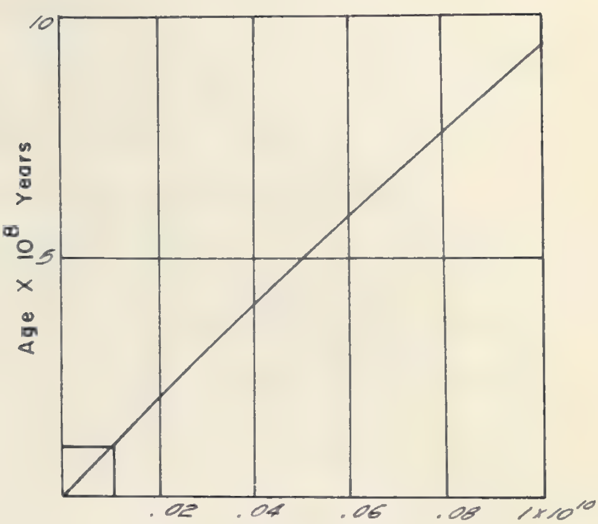
[illegible]

Figure 4



∝ ALPHAS/MG.
RADIATION DOSAGE
After Hurley and Fairbairn

Figure 5



F = YEARS
After Beveridge

of $35 \times 10^{13} \alpha$/mg. for total radiation dosage.

Using decay constants reported by Hankama (1954), Beveridge (1956) constructed a plot (figure 5) for equation (2) so that any value of t for an unknown zircon of know F, could be readily obtained.

Using the equation $\delta = AF$ with the present data, F was calculated as follows:

$$F = \frac{35 \times 10^{13} \alpha/\text{mg.}}{31 \times 10^{5} \alpha/\text{mg./year}}$$

$$F = 0.011 \times 10^{10} \text{ years.}$$

Applying this value of F to figure 5, the age (t) of the Kneehills zircon was read directly as 110 ± 50 million years.

The main sources of error are:

(a) A possible error of 19 percent in the alpha activity is sufficient to either increase or decrease the age result by 10 million years. This, of course, is based on the assumption that the conversion of beta to alpha counts is valid.

(b) An error of 0.02 degrees in the measurement of the diffraction angle 2θ could produce a maximum error of $\pm$ 40 million years for this region on the 2θ versus radiation dosage curve.

If an age of 110 million years for the Kneehills tuff is plotted on Holmes physical time scale (figure 6), the point corresponds to late lower Cretaceous. Strong paleontologic and stratigraphic evidence, however, places the Kneehills in the late Cretaceous. The age of the Cretaceous-Tertiary boundry according to Holmes scale is approximately 60 million years. The tuff, being somewhat older than this, should be between 60 and 70 million years old. It appears, then, that the calculated age on the

basis of radiation damage is about 45 million years too high but within the limits of error in the measurements involved.

AGE OF THE ARDLEY COAL SEAM

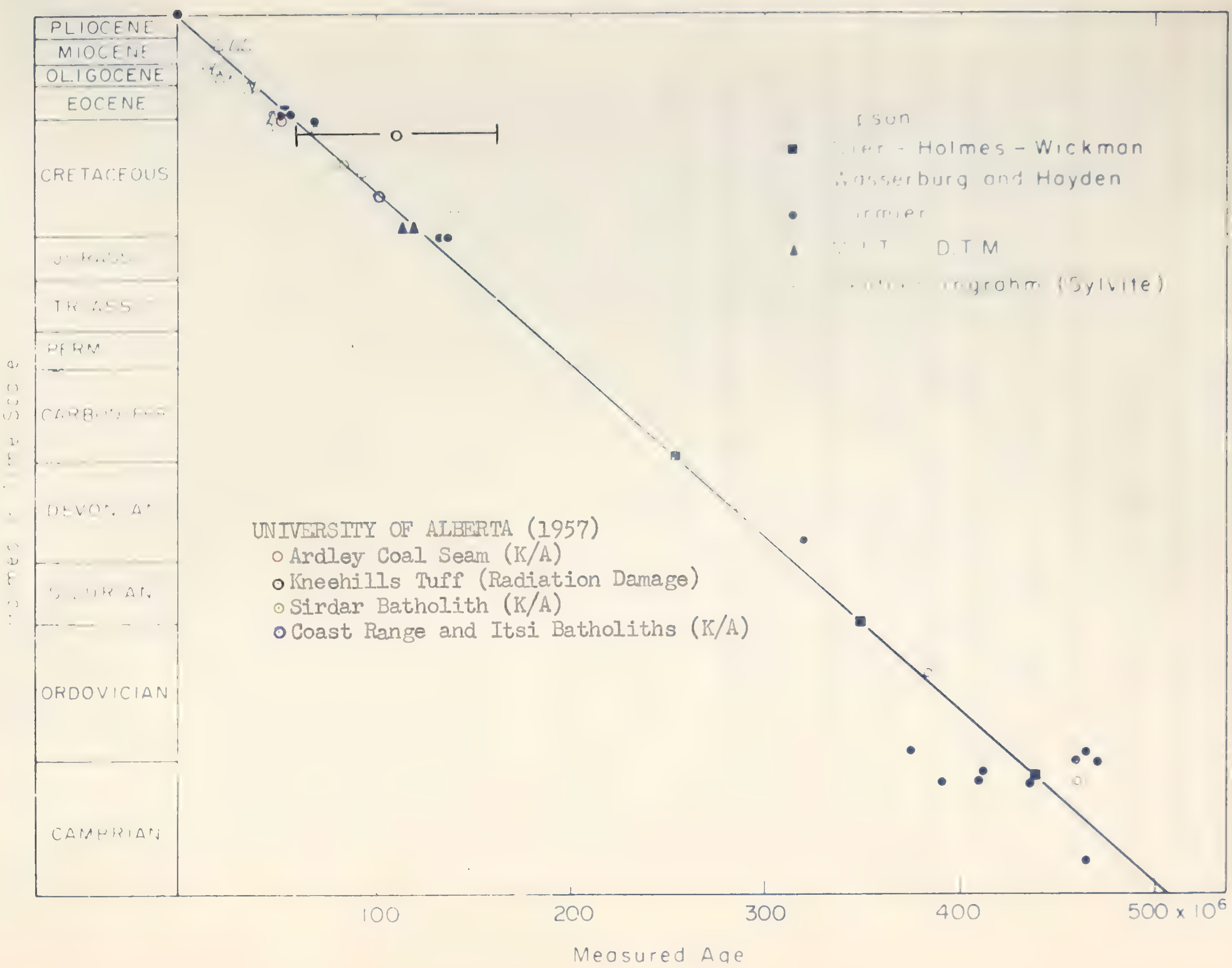
A 3 to 4 inch volcanic ash bed occurs near the top of the Ardley coal seam at Sissor's mine near Ardley, Alberta. The grit fraction was separated from a sample of the bentonite with the intent of obtaining a potassium - argon age determination on the feldspar therein. Attempts to separate the quartz from the feldspar using heavy liquids met with only moderate success.

Under the microscope the feldspar is colorless, fresh, angular and comprises a single variety with an average grain size of 0.05 mm. Twinning is rare. The index of refraction is somewhat less than Canada balsam (1.54). The mineral is optically negative and has an estimated 2V of 40 to 50 degrees. The sample contains 0.98 percent by weight potash and 2.00 percent soda as determined by flame photometry. This indicates a two to one ratio of sodium to potassium in the feldspar.

The feldspar mineral best fitted to the above description is anorthoclase.

About 8 grams of the mixed quartz - feldspar sample were sent to P. H. Baadsgaard, University of Minnesota for a potassium-argon age determination. Baadsgaard reported an age of 52 m.y. This figure is based on a potash content of 1.44 percent determined gravimetrically at the University of Minnesota, a figure considerably higher than the 0.98 percent value obtained using flame photometry at the University of Alberta. In the absence of additional sample, checks could not be made, but it is felt that the gravimetric result is more likely to be correct.

Figure 6.


PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
CRETACEOUS
ORDOVICIAN
CAMBRIAN
Holmes - Wickman
Wasserburg and Hayden
D.T.M
(Sylvite)
UNIVERSITY OF ALBERTA (1957)
Ardley Coal Seam (K/A)
Kneehills Tuff (Radiation Damage)
Sirdar Batholith (K/A)
Coast Range and Itsi Batholiths (K/A)
100
200
300
400
500×10^6
Measured Age

A correction for argon diffusion in the fine-grained anorthoclase (average diameter of 0.05 mm.) should be applied. Recent diffusion coefficient data are given by Reynolds (1957). If the correction were applied, the potassium-argon age would be older, and might correspond more closely to the predicted age based on Holmes' time scale (figure 6).

Dinosaurian remains of Lance age have been found 45 feet below and 90 feet above the Ardley seam (Sternberg, 1947-48). The Ardley seam occurs above the uppermost tuff lens of Kneehills type and seems to mark an end to the influx of this type of pyroclastic material.

The stratigraphic position of the coal seam renders this age date a contribution toward establishing a reliable absolute age for the critical Cretaceous - Tertiary boundary.

CHAPTER SIX

PROVENANCE

Sanderson (1931) suggested three possible sources for the volcanic ash beds occurring at various intervals in the Cretaceous strata of Alberta:

(1) That they originated from volcanic necks underlying the plains area which are now obscured by overlying Tertiary strata and consequently have escaped notice.

(2) That they had their source in the west, as suggested by the presence of the thick, relatively coarse grained Saunders tuff in the foothills.

(3) That volcanic necks reported in Kansas, Arkansas, Missouri, Wyoming and Montana contributed large amounts of volcanic material to the Cretaceous sediments of Alberta.

The first of these possibilities now seems an unlikely source for the Kneehills tuff since no volcanic features have ever been reported from the wealth of subsurface data subsequently accumulated. It seems rather improbable, with the present extensive subsurface exploration methods, that such a feature, if present, would escape notice; the possibility of complete removal by subsequent erosion is unsupported.

The main objection to a western source stems from the absence of volcanic rocks in the Rocky Mountain region except for the Crowsnest agglomerates and tuffs occurring at the top of the lower Cretaceous sequence (MacKenzie, 1956). However, the mountains in central British Columbia west of the Rockies were in a region of strong volcanic activity during the Tertiary (Armstrong, 1946). Earlier periods of volcanism may have existed. The relatively coarse grained foothills tuff beds may have had their source in this direction.

Radioactive age dates for several intrusive bodies of the Cordillera show that mid-Cretaceous time was a major period of igneous intrusion (Beveridge and Folinsbee, 1957). This conclusion has been recently strengthened by three additional potassium-argon age determinations on biotite from granitic intrusives from different areas. These ages were determined by P. H. Baadsgaard, University of Minnesota and are as follows:

Sirdar batholith near Cranbrook, B.C. (Bayonne batholith) Long. 116° 40' W, Lat. 49° 50' N.	*82 m.y.
Coast Range batholith at Horseshoe Bay Near Vancouver, B.C. Long. 123° 15' W, Lat. 49° 20' N.	105 m.y.
Itsi batholith, Yukon Territory Long. 130° 00' W, Lat. 63° 00' N.	102 m.y.

This evidence suggests that the major igneous intrusives in British Columbia were emplaced prior to Kneehills time hence it appears improbable that the tuff is related to volcanic rocks associated with these intrusives.

The third and most likely source of the Kneehills tuff is to the south, particularly in Montana. Areal uniformity in grain size of the tuff provides no clue with respect to direction of source but the fineness does suggest a distant source. Volcanic activity associated with the Boulder batholith as a possible source is considered in the paragraphs to follow.

Various ages have been tentatively assigned to the Boulder batholith in the past. On the basis of field evidence the batholith was emplaced sometime between late Cretaceous and the beginning of the Oligocene (Knopf, 1957). Physical age dating has added much strength to a late Cretaceous age first suggested by Knopf (1913). Orthoclase feldspar from

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* These ages were calculated using a branching ratio of 0.118.

a pegmatitic veinlet in the quartz monzonite of the Boulder batholith returned an age of 71 million years (Beveridge and Folinsbee, 1957). Lead-alpha dates on the zircon from the quartz monzonite gave ages of 69 and 71 m.y. Zircon from a sample of alaskite from Elkhorn Peak, which is a later phase, gave 61 m.y. (Chapman, Gottfried and Waring, 1954). These figures were arrived at independently and are in good agreement. From the standpoint of age, then, it is quite probable that the late Cretaceous Kneehills tuff was deposited synchronously with some stage in the emplacement of the Boulder batholith.

The Boulder batholith was thought by early workers to be simply a single magma intrusion. Knopf (1957) has shown it to be a composite body built up by five or six successive intrusions, becoming increasingly more silicic. The fifth intrusion is a medium grained biotite granite which clearly intrudes the earlier granodiorite. Aplite dikes up to 40 feet in thickness are known to cut the biotite granite and these are considered to represent a still later stage in the evolution of the batholith.

Weed (1912) mapped intrusive and extrusive rhyolites in the Butte district as two distinct types. The extrusive rhyolites are in part the products of volcanic outbursts. The intrusives occur mainly in dikes having a north-south trend. In reference to these dykes, Weed states "A few of them are directly traceable to Big Butte as a centre of eruptive activity, and all of them are believed to be off-shoots from this vent". A volcanic vent such as this is probably localized by fractures produced by the influence of an underlying cupola on the batholith similar to the plutonic cupolas of Daly (1914). These rhyolitic rocks are related to Knopf's later more silicic intrusive stages of the batholith. A chemical analysis of a sample of rhyolite from the Hyde Park dike, south of Silver

Creek, Butte, Montana given by Weed (1912) shows similarity to that of the Kneehills tuff:

	Hyde Park Rhyolite	Kneehills Tuff
SiO_2	74.34	87.81
Al_2O_3	12.97	5.54
Fe_2O_3	0.75	0.68
FeO	0.54	0.24
MgO	0.86	0.51
CaO	0.85	0.51
Na_2O	2.49	0.77
K_2O	4.72	0.84
TiO_2	0.18	0.54
P_2O_5	0.07	Trace
MnO	Trace	0.004
Co_2	-	0.09
BaO	0.07	-
SrO	Trace	-
ZrO	0.05	-
H_2O+	-	1.11
H_2O-	-	1.24
H_2O at 110°C	1.11	-
	100.03	99.88

Petrographic studies of a post Boulder batholith rhyolite sample from Butte (#19) showed the presence of about 10 percent biotite. The biotite accounts, in part, for the high potash content in the above rhyolite analysis relative to the Kneehills tuff. High feldspar content accounts for the remaining potash discrepancy and would also account for the high alumina and soda as compared with the Kneehills analysis. The presence of secondary silica is responsible for the high silica content in the Kneehills tuff. By using comparative data similar in part to the foregoing, Bystrom (1956) was able to eliminate a previously proposed source for Ordovician bentonite beds at Kinnekulla, Sweden.

It is suggested that the biotite, which should be present in the Kneehills tuff if it is genetically related to the rhyolite, was slightly delayed in settling by virture of its tabular habit. This is indicated by the

[illegible]

[illegible]

[illegible]

presence of abundant biotite in thin light coloured zones overlying each of the three beds at Strawberry Creek (Byrne, 1951). That these thin zones were part of the original ash fall was confirmed by the result of a study and comparison of their zircons given in an earlier chapter. This biotite related to the tuff is leached and, compared to the biotite from the rhyolite, is much finer grained. An x-ray diffraction pattern indicates that the biotite above the Kneehills tuff is altering to vermiculite. In the absence of other detailed field studies it is not known if these thin light coloured bentonite zones overlying the tuff at Strawberry Creek are present in other Kneehills outcrop localities.

As shown in a previous chapter, the heavy mineral suites of the Kneehills tuff and the rhyolite sample are similar. A comparison of their zircon crops suggest a petrogenetic relationship; this is illustrated in plates 3 and 4. Zircons from both rocks flouresce with a characteristic pale yellowish orange color under short wave ultra violet radiation (2537 Å) and not at all under long wave radiation (3650 Å). The rare hyacinth grains in the tuff showed no flourescence under either lamp; this is in accord with Wilson's (1950) observations.

Zircon crystals from the rhyolite, however are larger than those from the Kneehills tuff. Perhaps the physical conditions of an explosive phase of the magma having the same chemical composition as the rhyolite were such that they promoted growth of smaller crystals which were subsequently deposited with the Kneehills ash. On the other hand, if larger crystals were present at the time of the volcanic outbursts, it seems likely on the basis of studies made on recent dust storms by Chepil

(1957), that the zircons having breadth measurements greater than .06 mm. would settle out before reaching the area where the Kneehills tuff is presently found. It is interesting to note that the average grain size in the grit fraction of the volcanic ash bed in the Ardley coal seam is 0.05 mm., also indicating early settling of large particles.

On the basis of the evidence at hand, it is suggested that the upper tuff horizons as well as the Kneehills tuff are genetically related to a late effusive phase of the Boulder batholith.

DEPOSITION

Butte, Montana is 800 miles from the northernmost known exposure of Kneehills tuff at Whitcourt, Alberta. In the light of information pertaining to recent volcanic explosions, it is not necessary to invoke unusual conditions to account for this distance of ash transport. From the great Tombora eruption on the Island of Sambawa in 1855 two feet of ash settled at a distance of 850 miles from the vent (Marten, 1913). When Krokatoa erupted in 1883, fine volcanic dust encircled the world (Holmes, 1946). Dust falls from the 1912 explosion of Mount Katmai on the Alaska peninsula settled over 200 miles from the vent with such rapid deposition that it caused great destruction of life (Capps, 1915). Mount Trident in Katmai National Monument, Alaska became violently active for several days in 1953 with a series of explosions hurling clouds of steam and ash to altitudes of 30,000 and 35,000 feet (Muller, et al, 1954).

Considering an area of 80,000 square miles and assuming an

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[illegible]

average thickness of 3 inches for the tuff in Alberta, the source volcanic area is called upon to contribute 4 cubic miles of ash. It is realized that the material near source is not considered in the estimate. By way of contrast, Williams (1941) could account for only 14 out of 17 cubic miles of coarse volcanic debris which must have formed the original structure of what is now the Crater Lake caldera in Oregon. The remainder may have been fine material sent into the air and carried away by the wind. Pliestocene tuffs derived from volcanism connected with the caldera partly occupied by Lake Toba, Sumatra are thickly distributed over 7,000 square miles of Sumatra. They are 10 to 15 feet thick even in Malaya. The total volume of tuff is estimated at 300 cubic miles (Holmes, 1946).

Meteorological conditions in late Cretaceous time may have favoured a northward movement of any airborne Kneehills ash. The climate at that time by floral evidence was probably cool temperate, similar to the present climate in southern Ontario (Brayton, 1953). Continental conditions prevailed over much of western North America. Similar plants have been found in late upper Cretaceous sediments in the Arctic Circle indicating open water conditions in the Arctic region all year around. Assuming warm to semi-arid conditions in the area south of Montana as opposed to cooler temperatures in the Arctic, it seems likely that warm south winds would be frequent (Laycock, 1957).

The Kneehills tuff and the upper tuff horizons in the Drumheller area, by reason of mineralogic similarity, have a common source. The relationship of the Kneehills to tuff beds in the foothills is not clear.

They do not appear to be genetically related.

The occurrence of three or four closely spaced thin tuff lenses in the Kneehills interval at many localities represent separate ash falls from volcanic outbursts to the south. It is doubtful if any one explosion laid down a uniform layer of ash over the entire area. It seems reasonable that each of a series of renewed explosive eruptions resulted in deposition of ash over more or less broad areas whose extent was controlled by prevailing meteorological conditions; some of the areas overlapped.

Vague bedding features, small amount of contamination and the rather well preserved nature of the tuff leads to the conclusion that it was largely deposited in fresh water where it was protected from the action of winds. Swampy areas were probably common as indicated by the widespread occurrence of coal in the Edmonton formation. The present distribution and lensy character of the tuff was controlled in part by late Cretaceous topography; areas unprotected from the wind were either stripped or suffered loss of ash which later became incorporated with admixed clastics; low waterlain areas accumulated slightly thicker lenses.

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[illegible]

CONCLUSIONS

Results of the investigations presented herein show the Kneehills tuff to be remarkably uniform, both mineralogically and chemically, over a wide area of the Alberta sedimentary basin. It is related in origin to the upper tuff horizons in the Drumheller area but is not necessarily genetically related to tuff beds occupying similiar stratigraphic positions found in the Foothills area. The volcanic source of the latter could well be to the west. The Kneehills tuff was deposited synchronously with the emplacement of the Boulder batholith and appears to be derived from a pyroclastic extrusive phase of the late silicic stage in the evolution of the batholith. For the first time in the study of the Western Canada sedimentary basin, a direct relationship between a well dated bed in the sedimentary sequence and a specific igneous intrusive in the neighboring Cordillera has been established.

Age dating of the zircon from the tuff by the radiation damage method yielded an age of 110 m.y., which, relative to the Cretaceous - Tertiary boundary, is 45 m.y. too old. Although radiation damage is not a highly accurate method of dating, it is comparatively fast and has a useful application in relating the age of zircon in a sediment to an orogenic period as an aid in provenance studies.

A lead - alpha age on zircons from the Kneehills tuff determined by D. Gottfied of the United States Geological Survey is m.y.

Anorthoclase from a volcanic ash bed in the Ardley coal seam returned a potassium - argon age of 52 m.y. This value is in fair agreement with other dates quoted for the Cretaceous - Tertiary boundary.

Separate tuff lenses within the Kneehills zone represent separate

explosive outbursts at the source. The original ash, where preserved, was apparently laid down in fresh water. Deposition was followed by diagenetic leaching and alteration which resulted in enrichment of silica and the production of some montmorillonite.

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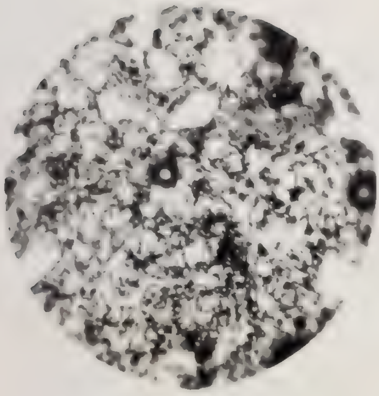
Tourtelot, H. A. (1957). The geology and vertebrate paleontology of upper eocene strata in the Wind River Basin, Wyoming; Smith. Misc. Coll., vol. 134, no. 4.

PLATE 1.

Photomicrographs of Tuffs

Magnification X 125

Nos. 1, 2, 3.	Kneehills tuff from Threehills Creek, Cypress Hills and Gleichen respectively; nicols uncrossed; fresh mineral fragments, mainly quartz and feldspar, set in a glassy matrix.
No. 4.	Saunders tuff, Coalspur; nicols uncrossed; large glass shards, one in the centre of the field shows vesicles.
No. 5, 6.	Late pre-Paskapoo tuff, Blackstone river; Nicols uncrossed and crossed respectively; abundant glass shards typically curved.



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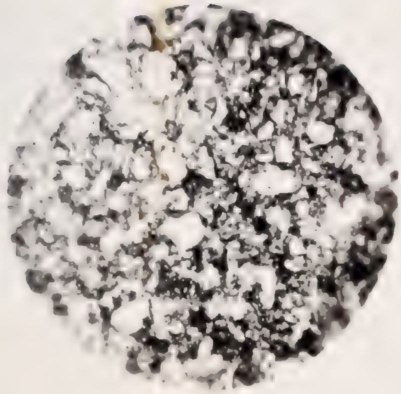

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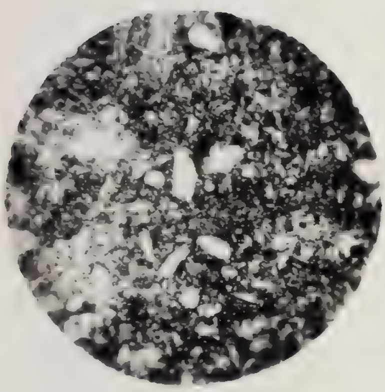

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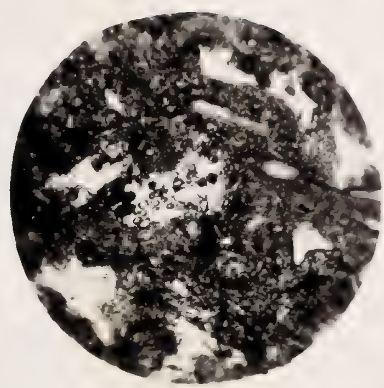

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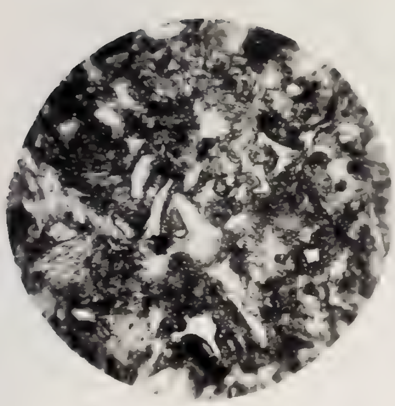


5

6

PLATE I

PLATE 2.

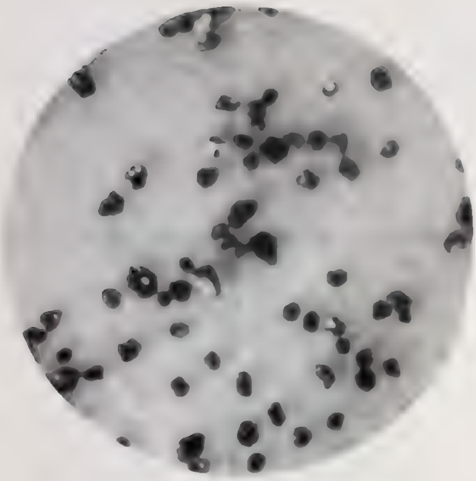
Ilmenite

No. 1. Euhedral ilmenite, Kneehills tuff, Threehills Creek.

No. 2. Euhedral ilmenite, rhyolite from Butte, Montana.

No. 3. X-ray diffraction pattern of ilmenite from Kneehills tuff.

No. 4. X-ray diffraction pattern of a known ilmenite from Arendal, Norway.



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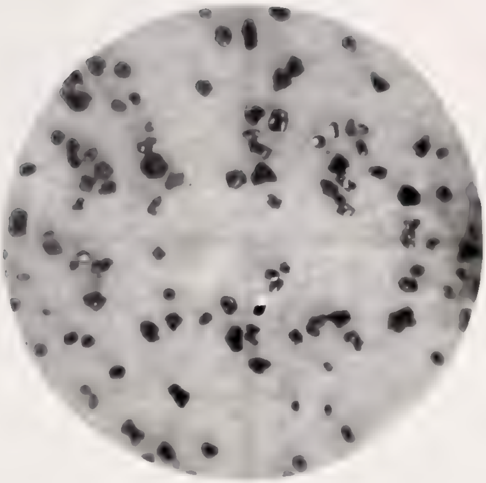

2

3

4

PLATE 2

PLATE 3.

Zircon Euhedra from the Kneehills Tuff

No. 1.	Actual length	.07 mm.	Simple euhedra, rod-shaped
No. 2.	"	.07 mm.	apatite and liquid or gas
No. 3.	"	.05 mm.	inclusions; No. 4 is
No. 4.	"	.09 mm.	corroded.
No. 5.	Actual length	.16 mm.	Long prismatic euhedra,
No. 6.	"	.13 mm.	inclusions as above; No. 6
No. 7.	"	.13 mm.	shows rounded terminations.
No. 8.	"	.16 mm.	
No. 9.	Actual length	.07 mm.	Stubby euhedra, inclusions
No. 10.	"	.07 mm.	common, complex terminations.
No. 11.	"	.05 mm.	
No. 12.	"	.07 mm.	

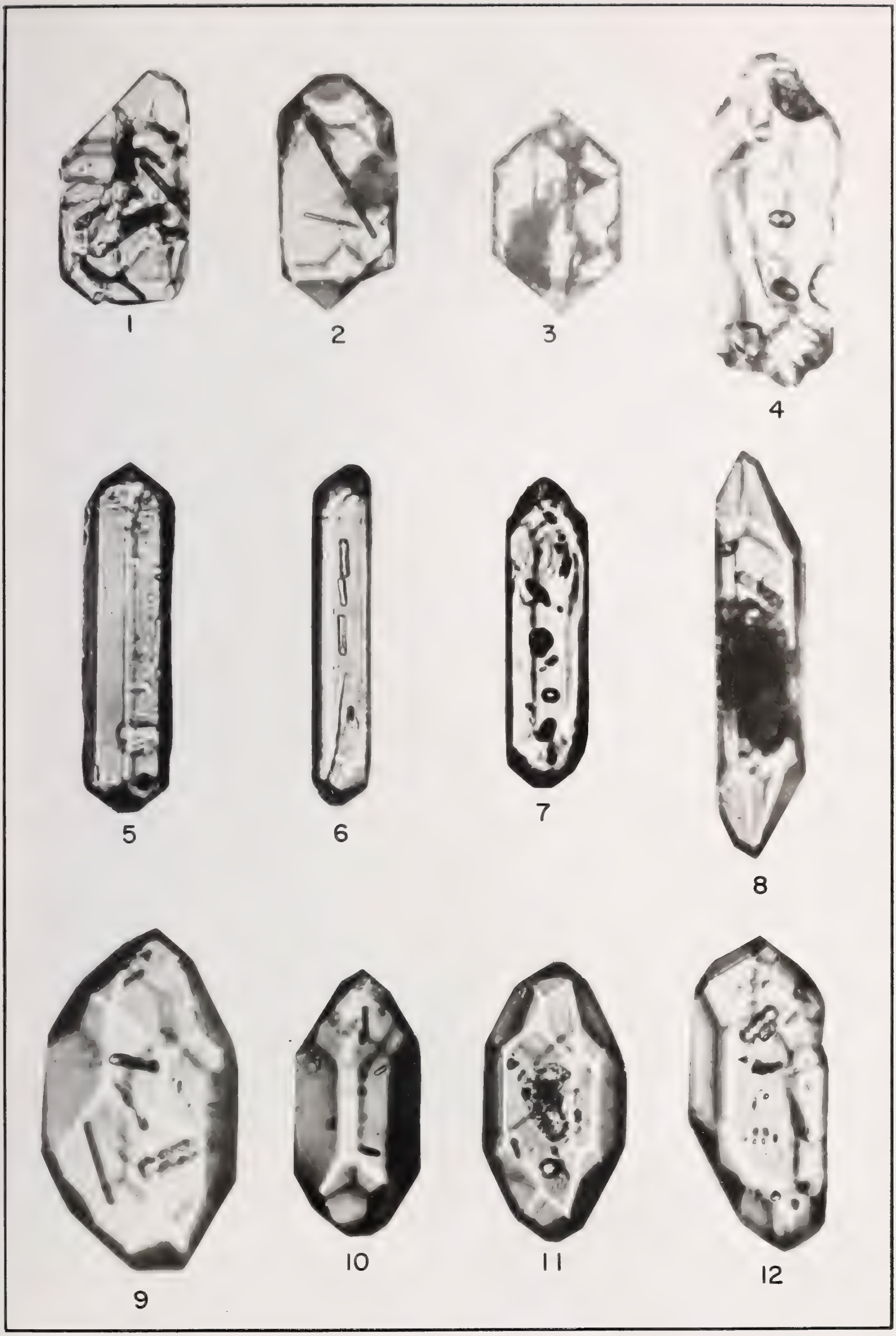

PLATE 3

PLATE 4.

Zircon Euhedra from Rhyolite Associated

With the Boulder Batholith

No. 1.	Actual length	.07 mm.	Simple euhedra, apatite and gas or liquid inclusions; No. 4 is zoned.
No. 2.	"	.10 mm.	
No. 3.	"	.16 mm.	
No. 4.	"	.13 mm.	
No. 5.	Actual length	.16 mm.	Long prismatic euhedra, inclusions abundant.
No. 6.	"	.22 mm.	
No. 7.	"	.25 mm.	
No. 8.	"	.16 mm.	
No. 9.	Actual length	.10 mm.	Stubby euhedra, few inclusions, complex terminations.
No. 10.	"	.13 mm.	
No. 11.	"	.10 mm.	
No. 12	"	.13 mm.	

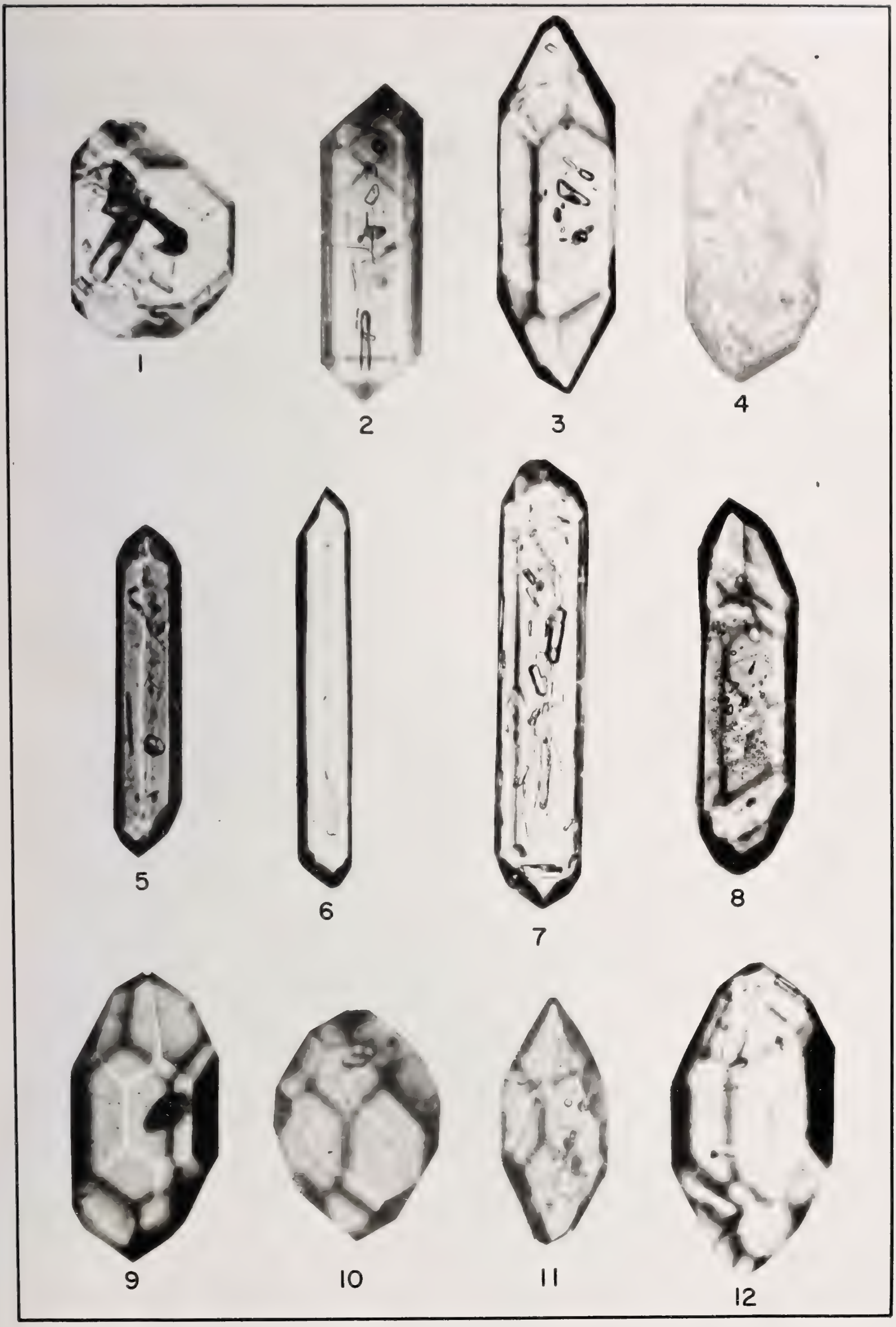

PLATE 4